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# Measurement of $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ using the BABAR detector

The BABAR Collaboration

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## Abstract

A preliminary measurement of the branching fraction $\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau)$ is made using $384.6\,\mathrm{fb}^{-1}$ of $e^+e^-$ collision data provided by the PEP-II collider, operating primarily at $\sqrt{s} = 10.58\,\mathrm{GeV}$, and recorded using the BABAR detector. From this we measure: $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau) = (0.840 \pm 0.004\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst}))\%$. This result is the most precise measurement to date and is consistent with the world average.

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# 1 INTRODUCTION

Hadronic $\tau$ decays provide a clean laboratory for studying the hadronic weak current. Hadronic products from $\tau$ decays give access to the light quark vector ($V$) and axial-vector ($A$) spectral functions, which give insight into the dynamics of QCD at intermediate scales as well as providing tests of the Standard Model itself [1].

For hadronic $\tau$-decays, $SU(3)_f$ symmetry breaking can be used to determine the Cabibbo-Kobayashi-Maskawa (CKM) matrix element magnitude $|V_{us}|$ [2], the strong coupling constant, $\alpha_S$, and the strange quark mass, $m_s$ [3]. These are all tests of the Standard Model as deviations from values measured in other processes would indicate new physics.

Hadrons from $\tau$ decays are produced via $W$ emission. Relative to non-strange ($ud$) currents, strange ($us$) currents of $\tau$ decays are suppressed by $(|V_{us}|/|V_{ud}|)^2 \simeq \tan^2\theta_C$, where $|V_{ud}|$ and $|V_{us}|$ are the absolute values of the CKM matrix elements. Resonant decay dominates these currents: the strange vector current is dominated by a $K^*$ resonance which decays to $K\pi$ and the strange axial-vector current by the $K_1$ which decays mostly via $K\rho$ and $K^*\pi$ to $K\pi\pi$.

The high luminosity provided by the PEP-II collider, coupled with a large $\tau^+\tau^-$ production cross-section near the operating energy of $\sqrt{s} = 10.58\,\text{GeV}$, provides a large data sample with which to study the strange hadronic decay $\tau^- \to (K\pi)^-\nu_\tau$ using the *BABAR* detector. Measurements of $\tau$ decay branching fractions to strange hadronic final states and studies of the strange spectral functions have been conducted by ALEPH [4], CLEO [5] and OPAL [6], but have been limited by statistics. About a hundred times larger samples of $\tau$-events have been provided by the $B$-factories *BABAR* and BELLE. The measurement of $\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau)$ was recently carried out by BELLE [7] with a significantly reduced uncertainty compared to that of previous measurements.

# 2 THE *BABAR* DETECTOR AND DATASET

The *BABAR* detector is described in detail in [8]. Charged particles are detected and their momenta measured with a 5-layer double sided silicon vertex tracker (SVT) and a 40-layer drift chamber (DCH) inside a $1.5\,\text{T}$ superconducting solenoidal magnet. A ring-imaging Cherenkov detector (DIRC) is used for the identification of charged particles. Energies of neutral particles are measured by an electromagnetic calorimeter (EMC) composed of $6,580$ CsI(Tl) crystals, and the instrumented magnetic flux return (IFR) is used to identify muons.

The analysis described in this paper is based on data taken using the *BABAR* detector at the PEP-II collider [9] located at SLAC in the data-taking periods between October 1999 and August 2006. During this period a total of $384.6\,\text{fb}^{-1}$ of data was recorded with a cross-section for $\tau^+\tau^-$ pair production of $(0.919 \pm 0.003)\,\text{nb}$ [15]. This data sample contains over 700 million $\tau$ decays. Monte Carlo (MC) studies of simulated signal and background events were carried out using various MC samples. The $\tau$ MC events studied were generated with KK2f [10] and decayed with TAUOLA [11] using $\tau$ branching fractions based on PDG 2006 [12]. In the MC, the $\tau^-$ decays to $K_S^0\pi^-$ via the $K^*(892)^-$ resonance with a branching fraction of 0.90%. Non-$\tau$ hadronic and dilepton MC samples are used for studying the non-$\tau$ backgrounds.

# 3 SELECTING $\tau^- \to K_S^0\pi^-\nu_\tau$ EVENTS

In this analysis events containing a pion and a $K_S^0$ in the final state are studied, where the $K_S^0$ is reconstructed in the $\pi^+\pi^-$ mode.

The event is divided into two hemispheres in the center-of-momentum system (CMS) using the plane perpendicular to the thrust axis, which is the direction which maximizes the sum of the longitudinal momenta of the neutrals and tracks in the event [16]. One hemisphere of the event is required to contain only one charged track; this is defined as the tag hemisphere. The other hemisphere is required to contain three charged tracks; this is defined as the signal hemisphere. The tag track and at least one of the signal hemisphere tracks are required to point towards the interaction point.

Approximately 35 % of $\tau$ decay to fully leptonic final states. Requiring the track in the tag hemisphere to be identified as an electron or muon while requiring the signal hemisphere to contain only hadrons strongly reduces backgrounds from $e^+e^- \to q\bar{q}$ events. Electrons are identified using the ratio of calorimeter energy to the track momentum ($E/p$), the ionisation loss in the tracking system ($dE/dx$) and the shape of the shower in the calorimeter. Muons are identified by hits in the IFR and small energy deposits in the calorimeter.

$K_S^0$ candidates are constructed from any two oppositely charged tracks with an invariant mass within 25 MeV/c$^2$ of the $K_S^0$ mass as given by the Particle Data Group (PDG) 497.672 MeV/c$^2$ [12]. Only events with exactly one $K_S^0$ candidate are retained. The track from the signal side not originating from the $K_S^0$ candidate is required to be identified as a pion and originate from the interaction point. Pions are identified by the ionisation loss in the tracking system ($dE/dx$), the shape of the shower in the calorimeter and their discrimination from kaons performed in the DIRC. All tracks on the signal side are required to lie within the geometrical acceptance region of the EMC and DIRC to ensure good particle identification.

Additional cuts are imposed to further reduce the backgrounds. The net charge of the event is required to be zero and a cut requiring the thrust of the event to be greater than 0.85 is imposed to reduce the non-$\tau$ background.

Backgrounds from Bhabha events are suppressed by requiring the momentum of the lepton-side track to be less than 4.9 GeV/c. Backgrounds from radiative Bhabha and $\mu$-pair events with a converted photon are suppressed by requiring the modulus of the cosine of the decay angle to be less than 0.97. The decay angle is defined as the angle between the momentum of the $\pi^+$ originating from the $K_S^0$ in the $K_S^0$'s rest frame and the $K_S^0$ momentum in the laboratory frame. When this quantity is calculated on electrons misidentified as pions the effect of assigning an incorrect mass will push the value towards $\pm 1$. From studies of missing transverse event energy, backgrounds from two-photon events are determined to be negligible.

Along with signal events, $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ events also produce three pions in the final state, but all three come directly from the primary interaction point. To remove $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ events the $K_S^0$ flight length significance in the plane perpendicular to the collision axis is required to be greater than 5.0. The flight length significance is defined as the measured flight length divided by its estimated uncertainty. This cut removes approximately 90% of the remaining $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ events in the sample. Figure 1 shows the $K_S^0$ flight length significance distribution for events in this analysis with all other cuts applied.

To increase the likelihood that the pions from the $K_S^0$ candidate really come from a $K_S^0$ they are required to have a distance of closest approach to each other of less than 2 mm. The $K_S^0$ trajectory is reconstructed by performing a vertex fit on the $K_S^0$ daughter pions constraining them to originate from a single point and then summing their momenta. To increase the probability that the $K_S^0$ originated from the interaction point this trajectory is required to have a distance of closest approach from the collision axis of less than 1 mm.

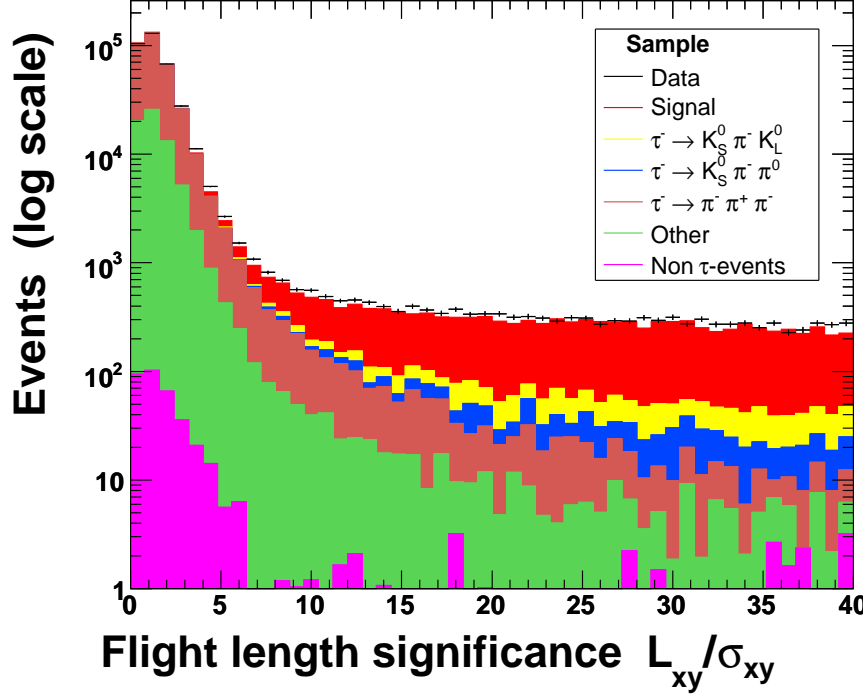Once these cuts have been applied, the largest two background channels are from $\tau^- \to$

Figure 1: The $K_S^0$ flight length significance in the $xy$-plane for the the combined ($e$-tag+$\mu$-tag) sample. The MC signal branching fraction is set to the measured value from this analysis.

$K_L^0 K_S^0 \pi^- \nu_\tau$ and $\tau^- \to K_S^0 \pi^- \pi^0 \nu_\tau$ events where the additional neutral particle to the $K_S^0$ is undetected. In order to reject such events maximum neutral energy cuts are applied. The total energy in the calorimeter not associated to any charged track must be less than 0.5 GeV. In the signal hemisphere this quantity is required to be below 0.25 GeV.

After selection about 80% of the retained MC events are $\tau \to K_S^0 \pi^- \nu_\tau$. About 98.5% of the background events come from $\tau$-decays and about 1.5% from non-$\tau$-events. The overall signal efficiency is estimated from the MC simulation as:

$$\varepsilon_{\text{sig}} = \frac{N_{\text{sig}}^{\text{sel}}}{N_{\text{sig}}^{\text{gen}}}, \tag{1}$$

where $N_{\text{sig}}^{\text{gen}}$ is the number of generated signal events and $N_{\text{sig}}^{\text{sel}}$ is the number of selected signal events. A total of $5.872 \times 10^6$ $\tau \to \bar{K}^0 \pi^- \nu_\tau$ signal events were generated.

The total selection efficiency, which includes the efficiency corrections that are described in Section 4, is $(0.620 \pm 0.003)\%$, $(0.482 \pm 0.003)\%$ and $(1.101 \pm 0.004)\%$ for the $e$-tag, $\mu$-tag and combined samples respectively.

# 4   EFFICIENCY CORRECTIONS

Since imperfect detector simulation may mean that the reconstruction/selection efficiencies differ between data and Monte Carlo, some corrections are applied to Monte Carlo signal and background events.

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A detailed study of the $K_S^0$ efficiency has been carried out. $B^0 \to \pi^+ D^- (D^- \to K_S^0 \pi^-)$ decays were used to study the $K_S^0$ efficiency for data and Monte Carlo. As a result of this study, a per $K_S^0$ average data/MC efficiency correction of 0.983 should be applied to the MC sample. Since only one $K_S^0$ is selected in this analysis the MC sample is weighted with 0.983 as a $K_S^0$ efficiency correction.

The efficiency of particle identification (PID) cuts are known to differ between data and Monte Carlo and so corrections to the Monte Carlo are applied. A set of efficiency tables, binned in $p$, $\theta$ and $\phi$, are used in order to obtain the necessary weights to use to correct the Monte Carlo events. The efficiency correction (data/MC relative efficiency) and corresponding uncertainty is calculated for each track.

In this analysis charged PID selection is performed on the pion not originating from the $K_S^0$ and the lepton. The average values obtained for the corrections due to the electron, muon and pion are 1.015, 0.948 and 0.979 respectively.

The total data/MC efficiency correction, $\varepsilon_{\mathrm{corr}}$, is made by combining the efficiency corrections described above. $\varepsilon_{\mathrm{corr}}$ is used to weight the MC sample and the average values obtained are 0.977, 0.912 and 0.947 for the $e$-tag, $\mu$-tag and combined samples. The systematic error coming from this procedure is described in Section 5.

# 5   SYSTEMATIC UNCERTAINTIES

A number of systematic uncertainties have been considered. These are described below.

An error of 1.10% is included due to the $K_S^0$ efficiency correction procedure described in Section 4. When propagated through to the branching fraction measurement this gives a 1.40% systematic uncertainty on the branching fraction.

The tracking efficiency is susceptible to bias caused by physics data and MC simulation discrepancies. An error of 0.23% per track not originating from the $K_S^0$ is assigned to account for this. Tracking uncertainties from the $K_S^0$ daughters are included in the $K_S^0$ selection systematic. Each event contains two reconstructed charged tracks with correlated uncertainties, leading to a total tracking efficiency uncertainty of 0.46%. This gives a 0.58% systematic uncertainty on the branching fraction.

The total particle identification uncertainty that arises from the efficiency correction procedure described in Section 4 for the $e$-tag, $\mu$-tag and combined samples is estimated to be 1.05%, 1.33% and 1.18%, respectively. When propagated through to the branching fraction measurement this gives a systematic uncertainty of 1.45% for the $e$-tag, 1.68% for the $\mu$-tag and 1.50% for the combined sample.

The relative uncertainty associated with the $\tau^+\tau^-$ pair production cross-section and the BABAR luminosity determination is 0.65%, leading to a 0.83% systematic uncertainty on the branching fraction. A relative error is applied for uncertainty in the modelling of selection variables on which cuts are applied. The modelling efficiency uncertainty is estimated as 0.29%, leading to a 0.37% systematic uncertainty on the branching fraction.

The systematic uncertainty on the signal efficiency and branching fraction measurement due to signal Monte Carlo statistics is 0.51% for the $e$-tag, 0.66% for the $\mu$-tag and 0.37% for the combined samples. The error on the number of background events due to limited Monte Carlo statistics is 1.02% for $e$-tag, 1.12% for $\mu$-tag and 0.76% for the combined sample. This gives a systematic uncertainty on the branching fraction measurement of 0.28% for $e$-tag, 0.30% for $\mu$-tag and 0.20% for the combined sample.

Since a number of $\tau$ decay modes have not yet been precisely measured, particularly those modes which contain Cabibbo suppression factors, the branching fractions used as input to the Monte Carlo simulation come with an uncertainty which feeds into the total systematic error. In order to evaluate this a weighted-sum of the $\tau$ backgrounds is constructed using the Monte Carlo truth for $\tau$ Monte Carlo events passing the analysis selection criteria.

The branching fraction for the background mode $\tau^- \to K^- K^+ \pi^- \nu_\tau$ is taken from a recent BABAR collaboration measurement $\mathcal{B}(\tau^- \to K^- K^+ \pi^- \nu_\tau) = (0.1346 \pm 0.0010 \pm 0.0036)\%$ [14]. We predict the ratio $\mathcal{B}(\tau^- \to \pi^- K_S^0 K_L^0 \nu_\tau)/\mathcal{B}(\tau^- \to K^- K^+ \pi^- \nu_\tau)$ to be $0.50 \pm 0.05$ using an isospin relation [17]. This gives $\mathcal{B}(\tau^- \to \pi^- K_S^0 K_L^0 \nu_\tau) = (0.0673 \pm 0.0070)\%$ which is consistent with the PDG 2006 value $\mathcal{B}(\tau^- \to \pi^- K_S^0 K_L^0 \nu_\tau) = (0.112 \pm 0.030)\%$. All other background mode uncertainties are taken from the PDG 2006 [12]. The overall estimated uncertainty due to the $\tau$ backgrounds is given by:

$$\Delta^{\tau-\text{bkg}} = \sqrt{\sum_i \left( w_i \frac{\sigma_i}{\mathcal{B}_i} \right)^2}, \tag{2}$$

where $w_i$ is the fraction of selected background $\tau$ events of mode $i$, $\mathcal{B}_i$ is the branching fraction of mode $i$ and $\sigma_i$ is the uncertainty of $\mathcal{B}_i$.

Table 1 shows the weights and uncertainties of the $\tau$ background modes remaining in the selected $\tau^- \to K_S^0 \pi^- \nu_\tau$ sample. The resulting uncertainty attributed to the $\tau$ background modes ($\Delta^{\tau-\text{bkg}}$) is estimated as 4.99% on the number of background events and is consistent between each of the tagged samples. This leads to a 1.37% systematic uncertainty on the branching fraction.

Table 1: $\tau$ background uncertainties and their weights in the selected $\tau^- \to K_S^0 \pi^- \nu_\tau$ sample.

| Decay Channel | $w[\%]$ | $\frac{\sigma}{\mathcal{B}}[\%]$ |
|---|---|---|
| $\tau^- \to \pi^- K_S^0 \pi^0 \nu_\tau$ | 24.24 | 10.53 |
| $\tau^- \to K^- K_S^0 \pi^0 \nu_\tau$ | 0.57 | 17.54 |
| $\tau^- \to \pi^- \bar{K}^0 K_L^0 \nu_\tau$ | 41.16 | 10.38 |
| $\tau^- \to \pi^- \bar{K}^0 K_S^0 \nu_\tau$ | 0.18 | 20.83 |
| $\tau^- \to K^- \bar{K}^0 \nu_\tau$ | 2.64 | 10.46 |
| $\tau^- \to \pi^- \pi^0 \nu_\tau$ | 0.75 | 0.39 |
| $\tau^- \to 2\pi^+ \pi^- \nu_\tau$ | 23.65 | 0.89 |
| $\tau^- \to 2\pi^- \pi^+ \pi^0 \nu_\tau$ | 3.41 | 1.35 |
| $\tau^- \to K^- K^+ \pi^- \nu_\tau$ | 0.61 | 2.78 |
| $\tau^- \to K^- \pi^+ \pi^- \nu_\tau$ | 0.78 | 10.26 |

Table 2 summarises the main sources of systematic uncertainty in the analysis.

The relative systematic uncertainty on the branching fraction includes the individual sources described above when propagated through equation (3) taking into account correlations between the different components considered. The total systematic uncertainty on the branching fraction measurement is 2.73%, 2.87% and 2.72% for the $e$-tag, $\mu$-tag and combined samples, respectively.

# 6   BRANCHING FRACTION MEASUREMENT: $\mathcal{B}(\tau^- \to \bar{K}^0 \pi^- \nu_\tau)$

Figure 2 shows the invariant mass spectrum of the selected data and MC $K_S^0 \pi^-$ candidates in the combined ($e$-tag+$\mu$-tag) sample after all the analysis requirements, including efficiency corrections.

Table 2: Summary of the systematic uncertainties as they feed into the measurement of $\mathcal{B}(\tau^- \to K^0\pi^-\nu_\tau)$.

| Systematic | $e$-tag | $\mu$-tag | Combined |
|---|---|---|---|
| Tracking | 0.58% | 0.58% | 0.58% |
| $K_S^0$ Efficiency | 1.40% | 1.40% | 1.40% |
| PID | 1.45% | 1.68% | 1.50% |
| $\mathcal{L} \times \sigma_{\tau\tau}$ | 0.83% | 0.83% | 0.83% |
| Statistical efficiency error | 0.51% | 0.56% | 0.38% |
| MC background statistics | 0.28% | 0.30% | 0.20% |
| $\tau$ backgrounds | 1.37% | 1.37% | 1.37% |
| Modelling efficiency | 0.37% | 0.37% | 0.37% |
| Total | 2.73% | 2.87% | 2.72% |

In this plot, the signal MC sample is scaled using the branching fraction measured in this analysis: $\mathcal{B}(\tau^- \to K_S^0\pi^-\nu_\tau) = 0.420\%$. The data and MC sample disagreements can be ascribed to inadequate modelling of the $K^*$ resonances in the MC simulation. There is some evidence that the $K^*(892)$ mass has been underestimated in the MC simulation and of the existence of $K_0^*(800)$ and $K_0^*(1430)$ resonances which are not modelled [7]. However these discrepancies do not affect our result for the branching ratio.

The final result for $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ is estimated using the combined $e$-tag + $\mu$-tag sample, where the total number of events observed, estimated background level and efficiency are derived from the two tagged samples. As a cross-check, $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ is calculated for each tagged sample separately and the results obtained are in excellent agreement with the combined result.

The branching fraction $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ is estimated by

$$\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau) = \frac{1}{2N_{\tau\tau}} \frac{N_{\text{data}} - N_{\text{bkg}}}{\varepsilon_{\text{sig}}}, \tag{3}$$

where $N_{\tau\tau}$ is the total number of $\tau^+\tau^-$ pairs in the real data, $N_{\text{data}}$ is the number of selected events in real data, $N_{\text{bkg}}$ is the number of background events estimated from Monte Carlo sample and $\varepsilon_{\text{sig}}$ is the signal efficiency as defined in equation (1). The total number of $\tau^+\tau^-$ pairs in the data is given by

$$N_{\tau\tau} = \sigma_\tau \mathcal{L}_{\text{data}} = (353.4 \pm 2.3) \times 10^6, \tag{4}$$

where $\sigma_\tau$ is the $\tau^+\tau^-$ production cross-section at *BABAR* (i.e. $0.919 \pm 0.003$ nb) and $\mathcal{L}_{\text{data}}$ is the (integrated) real data luminosity (i.e. $384.6 \pm 2.2$ fb$^{-1}$).

Table 3 gives the numbers of real and simulated data events passing the selection criteria that feed into the $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ calculation. A result for the measurement of the branching fraction $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ is given in Table 4.

Figure 3 shows previously published measurements of $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$. It can be seen that this *BABAR* preliminary result is the world's most precise measurement.
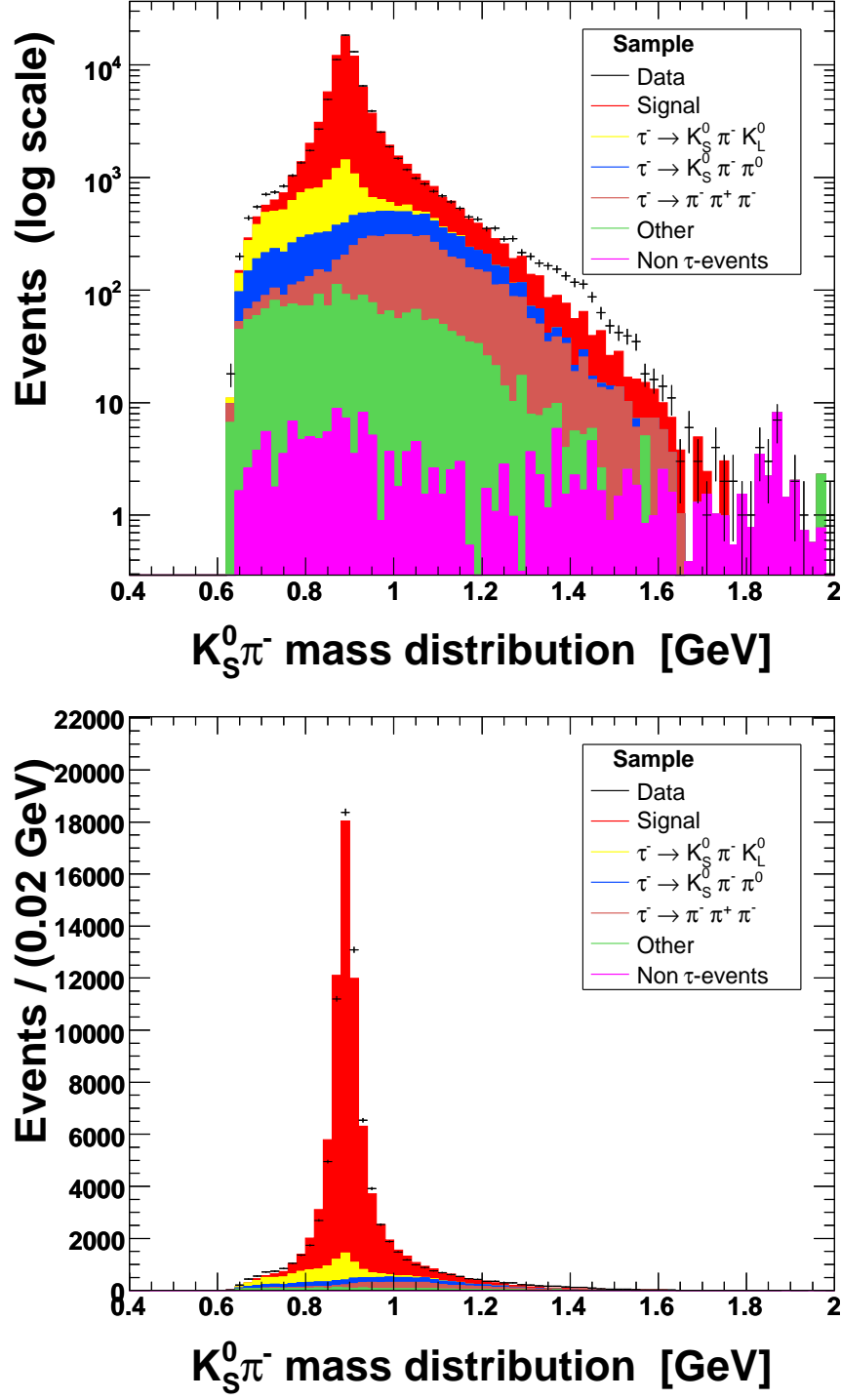
Figure 2: Reconstructed $\tau^- \to K_S^0 \pi^- \nu_\tau$ mass distribution for the combined ($e$-tag+$\mu$-tag) sample using (left) logarithmic scale and (right) linear scale. The MC signal branching fraction is set to the measured value from this analysis.
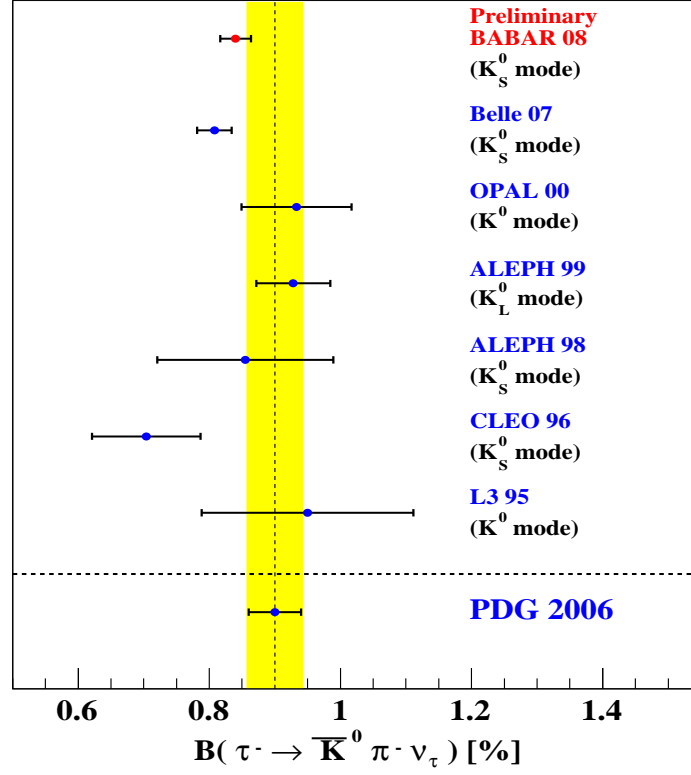
Figure 3: Previously published measurements of $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$. The Belle result and the result from this analysis do not contribute to the PDG 2006 average. The *BABAR* preliminary result provides the world's most precise measurement to date: $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau) = (0.840 \pm 0.004\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst}))\,\%$.

Table 3: Numbers of data and Monte Carlo events remaining in the selected samples corresponding to the $384.6\,\mathrm{fb}^{-1}$ (integrated) real data luminosity. The signal Monte Carlo has been scaled with the PDG 2006 value [12].

| Data | $e$-tag | $\mu$-tag | Combined |
|---|---|---|---|
| Real | $47092 \pm 217$ | $36641 \pm 191$ | $83733 \pm 289$ |
| Signal MC | $39445 \pm 193$ | $30749 \pm 176$ | $70194 \pm 261$ |
| $\tau^+\tau^-$ background | $9942 \pm 92$ | $7645 \pm 88$ | $17587 \pm 131$ |
| $uds$ | $8.9 \pm 3.4$ | $65.2 \pm 7.9$ | $74.1 \pm 8.5$ |
| $c\bar{c}$ | $45.5 \pm 5.0$ | $43.5 \pm 4.8$ | $89.1 \pm 6.9$ |
| $B\bar{B}$ | $3.4 \pm 1.1$ | $3.7 \pm 1.2$ | $7.1 \pm 1.6$ |
| $\mu^+\mu^-$ | $0 \pm 0$ | $14.2 \pm 3.7$ | $14.2 \pm 3.7$ |

Table 4: BABAR preliminary $\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau)$ measurements.

| Sample | $\mathcal{B}(\tau^- \to K^0\pi^-\nu_\tau)$ [%] |
|---|---|
| $e$-tag | $0.840 \pm 0.005\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst})$ |
| $\mu$-tag | $0.840 \pm 0.006\,(\mathrm{stat}) \pm 0.024\,(\mathrm{syst})$ |
| Combined | $0.840 \pm 0.004\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst})$ |

# 7 SUMMARY

Using $384.6\,\mathrm{fb}^{-1}$ of $e^+e^-$ collision data produced by the PEP-II collider and recorded by the BABAR detector, we obtain the preliminary result:

$$\mathcal{B}(\tau^- \to \bar{K}^0\pi^-\nu_\tau) =$$
$$(0.840 \pm 0.004\,(\mathrm{stat}) \pm 0.023\,(\mathrm{syst}))\,\%. \qquad (5)$$

This result is the most precise measurement of this branching fraction to date and is consistent with the world average.

# 8 ACKNOWLEDGEMENTS

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